# Production of High Harmonic X-ray Radiation from Non-linear Thomson Scattering at LLNL PLEIADES *

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*Abstract*

We describe an experiment for production of high harmonic x-ray radiation from Thomson backscattering of an ultra-short high power density laser by a relativistic electron beam at the PLEIADES facility at LLNL. In this scenario, electrons execute a "figure-8" motion under the influence of the high-intensity laser field, where the constant characterizing the field strength is expected to exceed unity: $a_L = eE_L/m_e c\omega_L \geq 1$. With large $a_L$ this motion produces high harmonic x-ray radiation and significant broadening of the spectral peaks. This paper is intended to give a layout of the PLEIADES experiment, along with progress towards experimental goals.

## INTRODUCTION

Novel x-ray sources based on the Thomson scattering between an ultra-short laser pulse and a high-brightness electron beam have been developed at different laboratories around the world [1, 2, 3, 4]. The capability of providing a femtosecond laser pulse based on the chirped-pulse amplification technology [5] and a low emittance, high-current, short-duration electron pulse based on the RF photoinjector [6] have enabled the production of high flux, ultra-short Thomson x-rays, which can be used in studying temporally resolved structural dynamics, biomedical imaging and x-ray protein crystallography. Such novel sources are currently based on the linear Thomson scattering mechanism, where the electron motion in the laser field undergoes a non-relativistic linear motion, producing quasi-monochromatic x-ray radiation in forward direction.

In the Thomson x-ray source, the number of x-ray photons produced is inversely proportional to the square of the electron beam spot-size at the interaction point (IP), $N_x \propto 1/\sigma_e^2$, and the optimization of the $\sigma_e$ can be explored to upgrade the x-ray beam brightness. At PLEIADES Thomson x-ray source facility, we have developed and implemented a novel electron beam focusing system based on the permanent magnet quadrupole technology arranged in a FODO triplet to obtain an order magnitude smaller electron beam spot area at IP [7]. The implementation of the system enhanced dramatically the electron density at IP, which provided a dramatic increase in the photon flux.

The number of photons scattered can also be increased via tight focusing of the incident laser at the interaction point, therefore providing more photons to interact with electrons. The laser intensity defined by $I_L[\mathrm{W/cm^2}] = 2P_L/\pi w_L^2$ shows that the incident photon density can be increased either through providing a larger laser power, $P_L$, or a smaller laser spot size, $w_L$. For the purpose of our planned experiment, we choose the laser spot size as our controlled parameter. From the intensity expression given above, a smaller laser produces a higher concentration of power in a small region such that the laser field strength defined by $a_L$ is increased. A normalized laser vector potential defined as a function of $I_L$ is given by $a_L = 0.85 \times 10^{-9}\lambda_L I_L^{1/2}$ where from this relation a non-linear condition $a_L \geq 1$ is manifested at sufficiently high laser intensity focused in a small region. In the non-linear Thomson regime, a high brightness optimization is impractical due to harmonic generation [8] and the depression in x-ray energy.

At $a_L \geq 1$ a strong laser field is established, and the magnetic field component of the laser becomes an effective contribution to the electron's longitudinal motion in addition to the transverse linear motions due to the electric field component. In the strong laser field limit, the electron trajectory exhibits a "figure-8" motion producing non-linear signatures: namely, a reduction in scattered x-ray energy as a function of laser potential $a_L$ and the generation of x-ray harmonics over a wide energy spectrum range. In this paper, the harmonic spectral distribution properties and the experimental scheme of the proposed non-linear Thomson experiment at the PLEIADES will be discussed.

## PLANNED NON-LINEAR THOMSON EXPERIMENT

The non-linear Thomson scattering experiment has been proposed at the PLEIADES (Picosecond Laser-Electron Inter-Action for the Dynamical Evaluation of Structures) facility [9, 10]. The PLEIADES facility is a high-brightness 10-100 keV Thomson x-ray source which employees a head-on (180 degrees) collision geometry between 54 fs infrared laser and a counter-propagating relativistic electron beam with energy ranging from 20 to 100 MeV. The PLEIADES system is composed of an S-band RF photoinjector with a dedicated UV Photoinjector Laser System (PLS), and a TW-class, 800 nm Ti:Sapphire, chirped-pulse amplification (CPA) laser system which delivers up to 500 mJ energy in a 54 fs Fourier transform-limited pulse to the Thomson interaction zone. The 81.557 MHz Kerr-lens mode-locked oscillator at the front end of

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Table 1: Non-linear Thomson experiment parameters

| Parameter | Value |
|---|---|
| Laser wavelength | 820 nm |
| Laser peak power | 10 TW |
| Laser rms radius | 9 $\mu$m |
| Laser periods | 20 |
| Electron beam energy | 40 MeV |
| Electron rms radius | 9 $\mu$m |
| Normalized emittance | 5 mm mrad |
| Energy spread | 2 % |
| Total electron charge | 300 pC |

the laser system serves as a master oscillator, which seeds both laser systems and maintains the synchronization of collision process. A 250-300 pC electron beam is produced via photo-emission from the Cu cathode surface excited by the 266 nm UV laser. A typical electron beam duration measurement is in the few picoseconds range. The electron beam exiting the photoinjector gun has an energy of 3.5 MeV and further accelerates up to 20-100 MeV through four 2.5 m, travelling wave sections.

The experimental chamber has been designed to contain both laser and electron optics necessary to produce small laser and electron beam spots at the interaction point for the production of the non-linear Thomson x-rays. The standard 60” (f/30) focal length parabolic mirror used in the linear Thomson x-ray production is to be replaced with a 12” (f/6) focal length parabolic mirror. The short focal length parabolic mirror is capable of production of tighter laser beam rms radius of approximately 9 $\mu$m, hence the laser potential parameter $a_L$ would exceed one. The counter-propagating 40 MeV electron beam to be collided with the high-intensity laser will be focused to a typical rms spot-size about 20 $\mu$m using the novel final beam focusing system developed at UCLA. The permanent magnet quadrupole (PMQ) final focusing system, which is currently in operation at PLEIADES, employs the two strong quads with 560 T/m field gradient and one weak quad with a reduced 260 T/m field gradient. The three individual PMQs are arranged in a triplet configuration in the final focusing system, which focuses the electron beam in both $x$ and $y$ transverse directions.

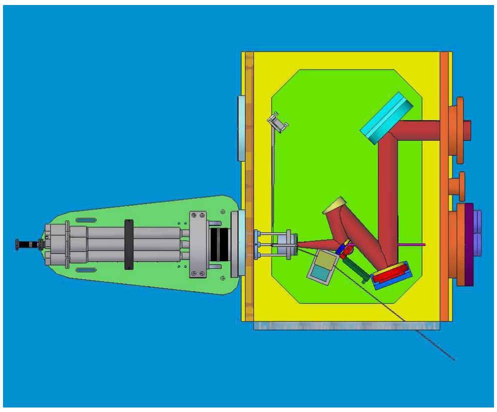

Figure 1: Non-linear Thomson scattering chamber layout (topview).

The two permanent magnet dipoles (PMD) based on high magnetization neodymium iron boride material will be used for the deflection of electron beams into the beam dump located outside and away from the experimental chamber. A single PMD is reconfigured into two smaller PMDs in the design scheme to fit inside the small experimental chamber to circumvent the interference with functions of optics. The combined PMDs produce a final electron beam deflection angle of 33 degrees through the 6” diameter port and into the beam dump pipe. The tapered PMD is designed to deflect the electron beam after the Thomson interaction to a 15 degree deflection angle. Since the tapered PMD is located a few centimeters after the IP, the magnet blocks need to be shaped exactly to allow the high-power, converging laser beam to propagate through safely avoiding damage to the magnet hardware. A varying gap with the installation of two slanted magnet blocks produces a varying longitudinal dipole profile where in the entrance electron beam sees the strong dipole field and gradually becomes weak at the exit side. The second C-PMD then further deflects the electron beam by 18 degrees. The beam dump site is approximately at 40 cm distance away from the experimental chamber and housed in a lead brick stacks to effectively shield the bremmsstrahlung radiation from interfering with the x-ray diagnostic instrument located just outside the experimental chamber in the direction of Thomson x-ray propagation.

A non-linear Thomson x-ray detection scheme employing the K-edge transmission measurements has been proposed. In the low $a_L < 1$ obtained by under-compressing the laser pulse, the x-rays tuned just above the K-edge is expected to produce the lowest transmission through a filter material. As the laser pulse is fully compressed back, the $a_L$ would exceed one and the x-ray energy is depressed below the K-edge line giving rise to an increase in x-ray transmissions. By employing a sensitive and fast gated x-ray camera, we expect the observation of the presence or absence of x-ray transmissions through a K-edge filter as the indication of non-linear effect.

## NON-LINEAR THOMSON SPECTRAL DISTRIBUTIONS

The far-field spectral distributions of non-linear Thomson x-rays backscattered from a single electron have been obtained utilizing the well-known mathematical solutions of undulator radiation emission [11]. By replacing the undulator parameter $K$ with $a_L$ having a laser period of $N_L$, the electron’s equation of motion in the strong laser pulse field can be obtained from the undulator physics. The radiation generated in FEL becomes dominantly non-linear when undulator strength $K$ exceeds one, which is also

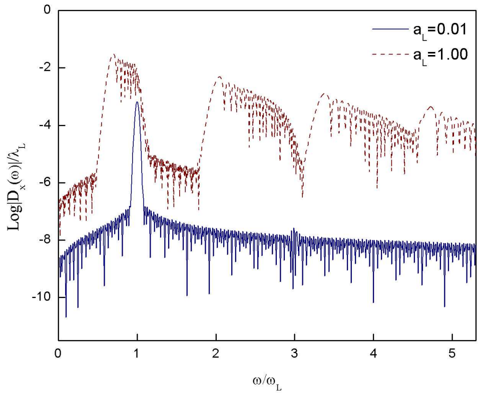


Figure 2: Non-linear Thomson spectral distributions: $a_L$= 0.01(bottom) and 1.0(top).

known as a wiggler. Similarly, non-linear Thomson effects are expected when $a_L$ increases above one and the average longitudinal velocity is decreased by a factor $1+a_L^2/2$. The reduction in the average electron's longitudinal velocity is manifested as a Doppler's downshift in frequency. In addition to the frequency downshift, the relativistic longitudinal motion induces phase delays giving rise to harmonic emission. Simulations have been carried out based on the theoretical formulation developed in [12], where the expected behavior is verified, as shown in the non-linear spectral distribution Fig. 2. In the calculation, a linearly polarized laser vector potential having the Gaussian envelope, $A(z,t) = a_L \cos\left(\frac{2\pi}{\lambda_L}(z+ct)\right) exp\left(\frac{5.6(z+ct)^2}{2\lambda_L^2 N_L^2}\right)$, is assumed, where $\lambda_L$ is the laser wavelength, and $N_L$ is a laser pulse period. In our non-linear spectral distribution calculations, we have used the following parameter values: $\lambda_L$=820 nm, $T_L$=54 fs, $\sigma_L$=18 $\mu$m, $\sigma_e$=18 $\mu$m, $\gamma$=80, $N_L$=20 and $\theta_{scatt}$=180 degrees. The spectral distribution curves shown are for $a_L$=0.01 (linear) and 1.0 (non-linear), and the on-axis observation direction showing odd harmonics. The linear spectral distribution shows a narrow spectral line at the fundamental $\omega_x = 4\gamma^2\omega_L$ as expected. Whereas the onset of harmonic spectral lines with the noticeable downshift in frequencies produced is shown for the $a_L$=1 where the even harmonics are partially seen. In addition to the expected non-linear effect, the broadening of harmonic spectral lines is visibly noticed in the spectral distribution. The observation of broadening effect is caused by ponderomotive scattering of electrons by high-laser field.

## THE CURRENT EXPERIMENT STATUS AND CONCLUSION

The linear Thomson x-ray source facility, PLEIADES, has successfully demonstrated its performance as a high brightness, ultra-short and energy tunable x-ray source. It employs various novel technologies such as the photoinjector system for production of low-emittance, high-charge electron beams, CPA Ti:Sapphire fs high-intensity laser system and the UCLA ultra-strong gradient PMQ final focus system for production of ultra-small 10-20 $\mu$m electron beams. The linear Thomson source produced at PLEIADES has enabled the studies of various different diffraction effects and probing various different heavy-metals.

Our next goal is the observation of the non-linear Thomson effect in the head-on collision of high-field laser with $a_L$ exceeding one and a high-density small electron beam. The theoretical study of this experiment revealed frequency downshifted harmonic lines with the ponderomotive broadening effect. A powerful mathematical formalism based on the FEL has been employed in the spectral distribution simulation code, which verified the mentioned expectations.

The necessary hardware such as the new short-focal length laser parabolic mirror, PMQ final focus system, PMDs, and other optical items have been designed and fabricated. The new beamline design has been reconfigured for the non-linear Thomson experiment.

A similar experiment has also been planned at UCLA Neptune Laboratory with the difference that the collision geometry is 90 degrees scattering angle, which employs 15 MeV electron beam and 500 GW $CO_2$ Mars laser producing soft x-rays [13].

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